

New bounds on neutrino electric millicharge from GEMMA experiment on neutrino magnetic moment

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Abstract

Using the new limit on the neutrino anomalous magnetic moment recently obtained by GEMMA experiment we get an order-of-magnitude estimation for possible new direct upper bound on the neutrino electric millicharge $|q_\nu| \sim 1.5 \times 10^{-12} e_0$ (e_0 is the absolute value of the electron charge) by comparing the neutrino magnetic moment and millicharge contributions to the total cross section at the electron recoil energy threshold of the experiment. This estimation is confirmed by the performed analysis of the GEMMA data using established statistical procedures and a new direct bound on the neutrino millicharge absolute value $|q_\nu| < 2.7 \times 10^{-12} e_0$ (90%CL) is derived. This limit is more stringent than the previous one obtained from the TEXONO reactor experiment data that is included to the Review of Particle Properties 2012.

Keywords:

1. Introduction

The importance of neutrino electromagnetic properties was first mentioned by Wolfgang Pauli just in 1930 when he postulated the existence of this

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particle and discussed the possibility that the neutrino might have a magnetic moment. Systematic theoretical studies of neutrino electromagnetic properties have started after it was shown that in the extended Standard Model with right-handed neutrinos the magnetic moment of a massive neutrino is, in general, nonvanishing and that its value is determined by the neutrino mass [1]. In spite of reasonable efforts in studies of neutrino electromagnetic properties, up to now there is no experimental confirmation in favour of nonvanishing neutrino electromagnetic characteristics. The available experimental data in this field do not rule out the possibility that neutrinos have “zero” electromagnetic properties. However, in the course of the recent development of knowledge on neutrino mixing and oscillations, supported by the discovery of flavour conversion of neutrinos from different sources, nontrivial neutrino electromagnetic properties, and nonzero magnetic moment in particular, are straightforward. It is also believed that studies of neutrino electromagnetic properties are important because they provide a kind of bridge (or “open a window”) to the new physics beyond the Standard Model. For the recent review on the neutrino electromagnetic properties see [2].

The neutrino electromagnetic properties are determined by the neutrino electromagnetic vertex function $\Lambda_\mu(q, l)$ that is related to the matrix element of the electromagnetic current between the neutrino initial $\psi(p)$ and final $\psi(p')$ states. The Lorentz and electromagnetic gauge invariance imply [2–5] that the electromagnetic vertex function can be written in the form:

$$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu - f_M(q^2)i\sigma_{\mu\nu}q^\nu + f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_\mu - q_\mu q)\gamma_5, \quad (1)$$

where where f_Q , f_M , f_E and f_A are charge, dipole magnetic and electric and anapole neutrino electromagnetic form factors. Note that the form factors depend only on q^2 which is the only independent Lorentz invariant dynamical quantity (the four-vector q is given by $q = p - p'$).

The electric charge is the charge form factor at zero q^2 . It is usually believed that the neutrino has a zero electric charge. This can be attributed to gauge invariance and anomaly cancellation constraints imposed in the Standard Model. However, if the neutrino has a mass, the statement that the neutrino electric charge is zero is not so evident as it meets the eye. In theoretical models with the absence of hypercharge quantization the electric charge also gets “dequantized” and, as a result, neutrinos may become electrically millicharged particles. A detailed discussion of theoretical models

predicted the millicharged neutrinos as well as possible experimental aspects of this problem can be found in many papers (see, for instance, [6] and more recent papers [7–10]), a review on this topic can be found in [2].

2. Order-of-magnitude estimation of bound on millicharge

The strategy of getting constraints on neutrino millicharge from the GEMMA reactor neutrino experiments is as follows [7]. Consider a massive neutrino with non-zero electric millicharge q_ν that induces an additional electromagnetic interaction of the neutrino with other particles of the Standard Model. Such a neutrino behaves as an electrically charged particle with the direct neutrino-photon interactions, additional to one produced by possible neutrino non-zero (anomalous) magnetic moment that is usually attributed to a massive neutrino. If there is no special mechanism of “screening” of these new electromagnetic interactions then the neutrino will get a normal magnetic moment:

$$\mu_\nu^q = \frac{q_\nu}{2m_\nu} \quad (2)$$

Thus, for a millicharged massive neutrino one can expect that the magnetic moment contains two terms,

$$\mu_\nu = \mu_\nu^q + \mu_\nu^a. \quad (3)$$

Now we consider the direct constraints on the neutrino millicharge obtained using data on the neutrino electromagnetic cross section in the GEMMA experiment. It is important to note that although in the case of a millicharged neutrino two terms, i.e. normal and anomalous magnetic moments, sum up in the total expression (3) for the magnetic moment, however these two contributions should be treated separately when one considers the electromagnetic contribution to the scattering cross section. The point is that the normal magnetic moment contribution is accounted for automatically when one considers the direct neutrino millicharge to the electron charge interaction. The expressions for the neutrino magnetic moment and millicharge cross sections are respectively,

$$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu^a} \approx \pi\alpha^2 \frac{1}{m_e^2 T} \left(\frac{\mu_\nu^a}{\mu_B}\right)^2, \quad (4)$$

and

$$\left(\frac{d\sigma}{dT}\right)_{q_\nu} \approx 2\pi\alpha \frac{1}{m_e T^2} q_\nu^2. \quad (5)$$

In case there are no observable deviations from the weak contribution to the neutrino scattering cross section it is possible to get [7] the upper bound for the neutrino millicharge demanding that possible effect due to q_ν does not exceed one due to the neutrino magnetic moment,

$$q_\nu^2 < \frac{T}{2m_e} \left(\frac{\mu_\nu^a}{\mu_B} \right)^2 e_0^2. \quad (6)$$

Note that the bound derived can be considered as an order-of-magnitude estimation for a possible sensitivity of the experiment to q_ν and a more accurate analysis implies account for experimental data taken over an extended energy range.

3. New bound on millicharge from GEMMA experiment

GEMMA (Germanium Experiment for measurement of Magnetic Moment of Antineutrino) investigates the reactor antineutrino-electron scattering at the Kalinin Nuclear Power Plant (Russia). The spectrometer includes a HPGe detector of 1.5 kg installed within NaI active shielding. HPGe + NaI are surrounded with multi-layer passive shielding: electrolytic copper, borated polyethylene and lead. As a result of 4-year measurement the world best upper limit on the neutrino magnetic moments has been obtained [11]

$$\mu_\nu^a < 2.9 \times 10^{-11} \mu_B. \quad (7)$$

Applying this result to (7) and taking into account that the effective threshold T is on the level of 2.8 keV we get [7] the upper bound on neutrino millicharge:

$$|q_\nu| \sim 1.5 \times 10^{-12} e_0. \quad (8)$$

The obtained constraint should be treated as a rough order-of-magnitude estimation, while the exact values should be evaluated using the corresponding statistical procedures. This is because the limits on the neutrino magnetic moment are derived from the GEMMA experiment data taken over an extended energy range from about 2.8 keV to 55 keV rather than at a single electron energy-bin at threshold.

To evaluate the limit on q_ν we use the final spectra from GEMMA. The difference between S_{on} and S_{off} taking into account S_{weak} normalized by the theoretical electromagnetic spectra S_μ^{th} can be interpreted as evaluation of

μ_ν and/or q_ν for each energy bin from the region of interest. The detailed procedure of data processing and obtaining the final result on μ_ν^a is shown in [11] and can be illustrated by Fig. 1. The procedure includes the differential

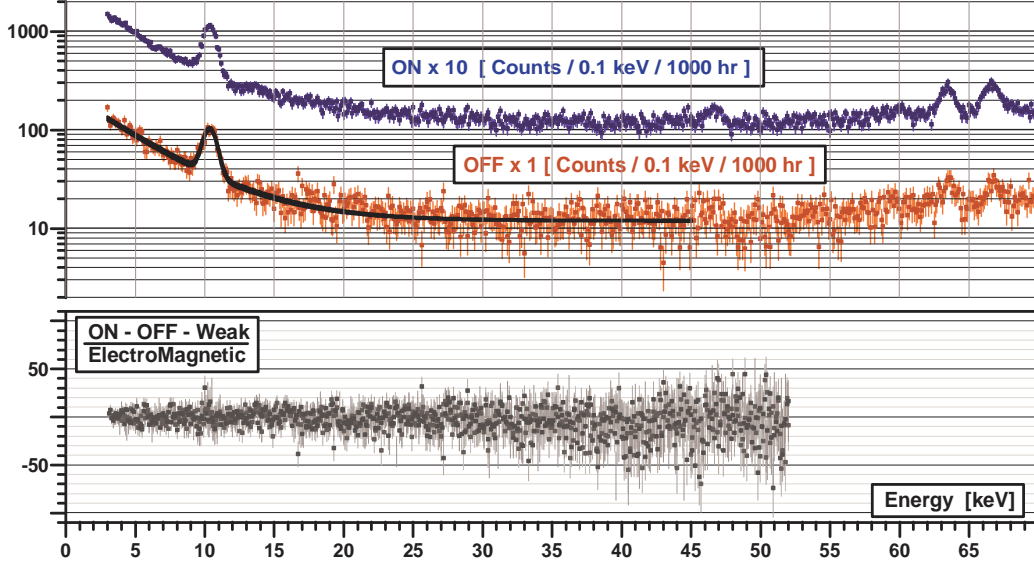


Figure 1: Experimental data of the GEMMA collaboration [11]. The difference $S_{on} - S_{off}$ taking into account S_{weak} normalized by the theoretical electromagnetic spectra S_μ^{th} .

method that provides equal pattern for ON and OFF spectra. The likelihood method is used to obtain the upper limit for an electromagnetic parameter. Following this procedure we obtain the limit [7]

$$|q_\nu| < 2.7 \times 10^{-12} e_0 \text{ (90\% C.L.)} \quad (9)$$

applying the developed procedure to the neutrino millicharge.

4. Future bounds on electromagnetic parameters in GEMMA

It is interesting to estimate the range of the neutrino millicharge that can be probed in a few years with GEMMA-II experiment that is now in the final stage preparation and is expected to get data in 2015. The experimental setup is being placed under the reactor unit No. 3 where the distance from the centre of the core is 10 m. In this way we double the antineutrino flux up to $5.4 \times 10^{13} 1/cm^2/s$. Furthermore, being equipped with a special lifting

mechanism the spectrometer will be moveable. The mass of the detector is increased by a factor of 4 (two detectors with a mass of 3 kg each). To avoid the “Xe-problems” the internal part of the detector shielding will be gas tight. A special U-type low-background cryostat is used in order to improve the passive shielding and thus reduce the external background in the ROI down to $\sim 0.5 - 1.0 (keV \times kg \times day)^{-1}$. A special care is taken to improve antimicrophonic and electric shielding. We also plan to reduce the effective threshold from 2.8 to 1.5 keV.

As a result GEMMA-II will be sensitive to possible electromagnetic parameters at the level:

$$\mu_\nu^a < 1.1 \times 10^{-11} \mu_B, \quad |q_\nu| \sim 9.4 \times 10^{-13} e_0. \quad (10)$$

For GEMMA-III with new generation detectors ($T_{th} \sim 350 eV$) the sensitivity will be even more improved,

$$\mu_\nu^a < 5.8 \times 10^{-12} \mu_B, \quad |q_\nu| \sim 5.5 \times 10^{-13} e_0. \quad (11)$$

Note that the obtained estimations for the expected sensitivities of the future GEMMA-II and GEMMA-III to the neutrino millicharge, Eqs. (10) and (11), are more conservative than the corresponding sensitivities obtained in [7]. This is because the expected sensitivities to q_ν of GEMMA-II and III are derived in [7] for a single electron energy-bin at the expected thresholds whereas here above we consider the expected extended energy ranges for the electron.

5. Conclusions

A new upper limit on the neutrino magnetic moment recently obtained by the GEMMA experiment allows us, by comparing the neutrino magnetic moment and millicharge contributions to the total cross section at the electron recoil energy threshold of the experiment, to get an order-of-magnitude estimation for possible new direct upper bound on the neutrino electric millicharge, $|q_\nu| \sim 1.5 \times 10^{-12} e_0$. This estimation is confirmed by performing an analysis of the GEMMA data using established statistical procedures that yields the new limit at the level of $|q_\nu| < 2.7 \times 10^{-12} e_0$ (90% *C.L.*) The obtained bound (10) on the neutrino millicharge from the recent experimental data of the GEMMA collaboration is more stringent than the reactor

neutrino scattering constraint included by the Particle Data Group Collaboration to the Review of Particle Physics [12] and that was obtained by [13] from the TEXONO reactor experiment data [14]. Accordingly, we predict that a new bound on the millicharge that can be obtained in future with the new GEMMA experiment data will be a factor of about 10 more stringent than one from the present GEMMA data. Finally, note that upper bounds on the neutrino electric millicharge on the level of $|q_\nu| \sim 10^{-12}e_0$ are also discussed in [15].

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